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Intermodulation between v.h.f./f.m. broadcast transmitters and the protection of adjacent-band aeronautical services

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INTERMODULATION BETWEEN VHF/FM BROADCAST TRANSMITTERS AND THE PROTECTION OF ADJACENT-BAND AERONAUTICAL SERVICES

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Summary

Mechanisms are described by which VHF/FM broadcast transmitters can intermodulate and radiate low-level signals which may lie in the adjacent aeronautical services band. Measurements of the levels of intermodulation products at typical stations are given and ways in which these may be reduced in the future are indicated. It is concluded that third-order intermodulation products radiated from the antenna can be kept at least 10 dB below the level corresponding to the ITU requirement without undue difficulty.

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1. Introduction

The decision of the World Administrative Radio Conference held at Geneva in 1979 to extend the VHF/FM broadcast band to 108 MHz put broadcasting and aeronautical radionavigation services in adjacent frequency bands. That this might lead to problems of interference was recognized in the agenda of the ITU Conference held in Geneva in 1982 to determine the technical constraints to be used in planning the new band, which specifically called for consideration to be given to the avoidance of interference to the aeronautical services.

The report of the 1982 Conference[1] describes the mechanisms by which interference can arise and gives conditions which it is thought will avoid interference. Two general types of interference are distinguished. Components radiated from the broadcast transmitter at or near the frequency of the aeronautical service constitute Type A interference whereas components generated within the aeronautical receiver constitute Type B interference. In the latter case remedial measures can be taken at the receiver; in the former they cannot.

In the normal operation of broadcast transmitters Type A interference may arise in two ways. First, the broadcast transmitters may intermodulate to produce terms in the aeronautical frequency bands; this is termed Type A1. Second, the sidebands of a broadcast transmitter may include non-negligible components in the aeronautical bands; this mechanism, which is designated Type A2, will in practice arise only from transmitters having frequencies near to 108 MHz and is not considered further in this report.

2. Aeronautical radio-navigation services at risk

2.1. ILS

The aeronautical service which is generally considered to be most at risk is that of the Instrument Landing System (ILS), operating in the frequency band 108-112 MHz. The Geneva Conference decided that a protection ratio of 17 dB was appropriate against f.m. broadcast interference; this is 3 dB more stringent than was found necessary for the worst receiver measured in UK tests, the additional margin being provided in order to make provision for multiple interference. The specified minimum field strength for Category I ILS is 40 μV/m or + 32 dB (μV/m) so that the maximum permissible level of a radiated intermodulation product (i.p.) co-incident in frequency with an ILS transmission is +15 dB (μV/m).

2.2. VOR

Another aeronautical service that may be affected is VOR (VHF Omnidirectional Range) which uses the frequency band 108-118 MHz. Advice from the Civil Aviation Authority is that interference to this service is unlikely to be as critical as that to ILS but this is not reflected in the Conference report which was that the same protection ratio should be used as for ILS pending further measurements. The minimum field strength for the VOR service is 90 μV/m or + 39 dB (μV/m) but the service areas are much greater than for ILS, more especially for those having frequency allocations in the 112-118 MHz frequency band.

2.3. VHF/Communications

The third aeronautical service is that of VHF Communications, which uses the frequency band 118-137 MHz. The Conference recommendation was again for a protection ratio of +17 dB and the minimum field strength specified for the service is 75 μV/m (+ 37 dB (μV/m)).

3. Intermodulation in a transmission system

When two or more transmission frequencies f_a, f_b are combined into one aerial system there is a possibility of intermodulation taking place somewhere in the transmission system. At VHF the intermodulation frequencies which are most likely to cause interference with other services are the third-order products[2] of the form $2f_a - f_b$ or $f_a + f_b - f_c$, because these frequencies remain in the VHF band and are therefore radiated efficiently by the aerial system. They are also more difficult to filter out than those which appear close to the harmonic frequencies.

Intermodulation at the transmitting station may take place either in the transmitters themselves

or in the subsequent transmission system. By the first process, illustrated for two transmitters in Fig. 1, the channel combiner may allow a low level of voltage from one transmitter (frequency f_a) to reach the output stage of another transmitter (frequency f_b) where mixing takes place to produce a frequency $2f_b - f_a$. Similarly, the frequency $2f_a - f_b$ is generated predominatly in the transmitter of frequency f_a. The levels of the

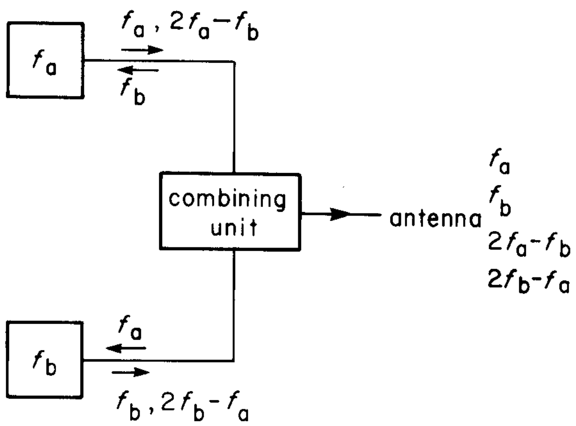

Fig. 1 — Combination of two transmitters.

products radiated are determined by:—

(i) the attenuation from one transmitter at its own frequency to the generating transmitter.

(ii) a conversion loss in the generating transmitter which is a function of the frequency separation between the two transmitters.

(iii) the attenuation from the generating transmitter to the antenna at the intermodulation frequency.

The corresponding three-transmitter case is illustrated in Fig. 2 with the transmitters having frequencies f_a, f_b and f_c. It is still possible for

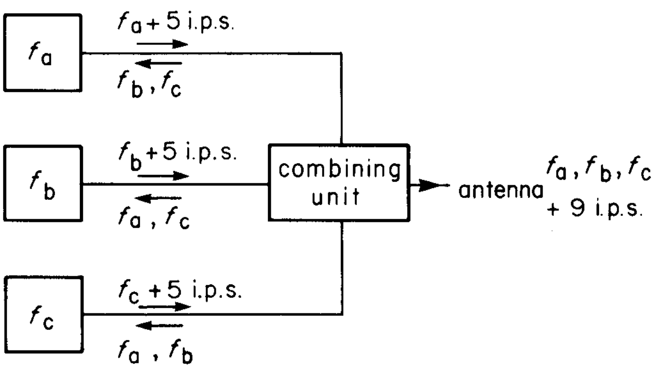

Fig. 2 — Combination of three transmitters.

pairs of transmitters to intermodulate to produce frequencies:—

$$2f_a - f_b \qquad 2f_a - f_c \qquad 2f_b - f_a$$
$$2f_b - f_c \qquad 2f_c - f_a \qquad 2f_c - f_b$$

However, a new mechanism becomes possible giving further third-order products:—

$$f_a + f_b - f_c \qquad f_a + f_c - f_b \qquad f_b + f_c - f_a$$

These three-frequency products will be generated in each of the transmitters at levels that are determined by the individual path losses through the combiner and a conversion loss that is not necessarily the same as for the two-frequency case. The levels reaching the antenna are the vector sum of these contributions. The estimation of the level of a three-frequency product is thus much more difficult than for a two-frequency product.

The majority of existing national-network frequency allocations within the U.K. are at three equally-spaced frequencies so that this case is of particular interest. Fig. 3 shows where the frequencies of the intermodulation products lie in relation to the transmitter frequencies. Some products have the same nominal frequency as the transmitters but, being at a much lower level than the wanted signal, are inaudible. There remain four frequencies on which intermodulation products fall, two above the transmitter frequencies and two below. The two outer ones are single products of the form $2f_c - f_a$. The two inner frequencies are each occupied by one two-frequency and one three-frequency product. These products, although of the same nominal frequency, are not synchronous, having small frequency differences that result from the transmitter frequency tolerances. Moreover, since the various transmitters may be carrying different programmes, the instantaneous frequencies would not be identical even if there were no frequency tolerance of the unmodulated carrier frequencies. Accordingly a measurement of the levels of the products on these frequencies would be of the power sum of the components.

The second process by which intermodulation may take place is in the transmission system after frequencies have been combined and may be due to arcing or to small non-linearity in the resistance of metal-to-metal contacts within the feeder and aerial system. In practice, however, the levels thus produced are usually found to be lower than those produced due to an imperfect channel

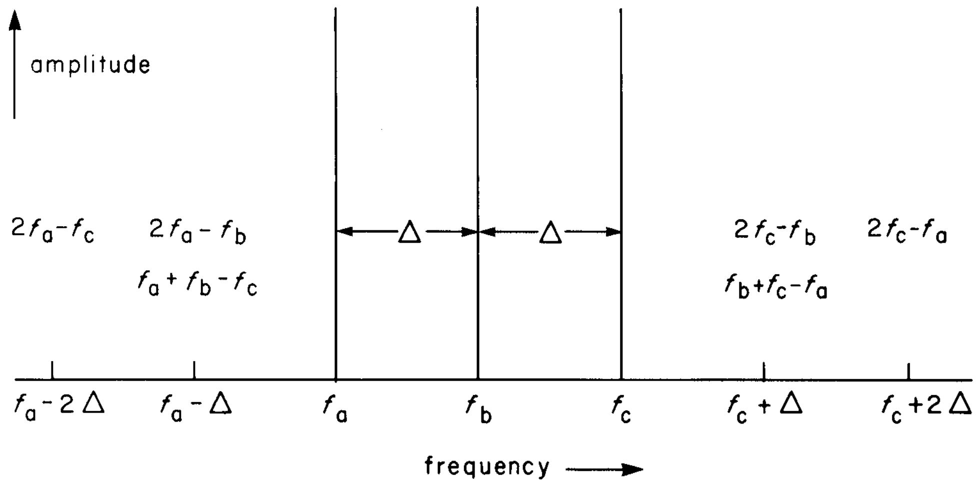

Fig. 3 — Occurrence of third-order intermodulation products at a three-frequency transmitting station with equally-spaced frequencies.

combiner. The possibility of intermodulation having taken place by the second process can be checked by comparing the levels of products measured in the radiated field with those measured in the main feeders.

4. Transmitter conversion losses

A knowledge of transmitter conversion losses is required in order to draw-up a realistic specification for the combining units. Details of measurements of the loss for the generation of two-frequency products are given in Fig. 4 for two types of high-power tetrode transmitters and for one type of low-power solid-state transmitter. The two high-power transmitters differ in the class of operation of the final stage (Wrotham is Class C, Sutton Coldfield is Class B) and this appears to be the reason for the difference of 8 dB in the conversion loss. The marked increase of conversion loss with frequency separation is attributed to the tuning of the final amplifier.

Measurements of the conversion to three-frequency products were made on one of the Sutton Coldfield transmitters. These products were very weak and near to the sensitivity limit with conversion losses exceeding 50 dB.

The arrangement used for these measurements is shown in Fig. 5. The output of the transmitter was divided by a 3 dB coupler, the fourth port of which was used to inject the second and third frequencies. The levels of these going into the transmitter, and the levels of the intermodulation products coming out, were measured on the directional probes fitted to the transmitter.

5. Transmitter combining units

There are several different types of unit in

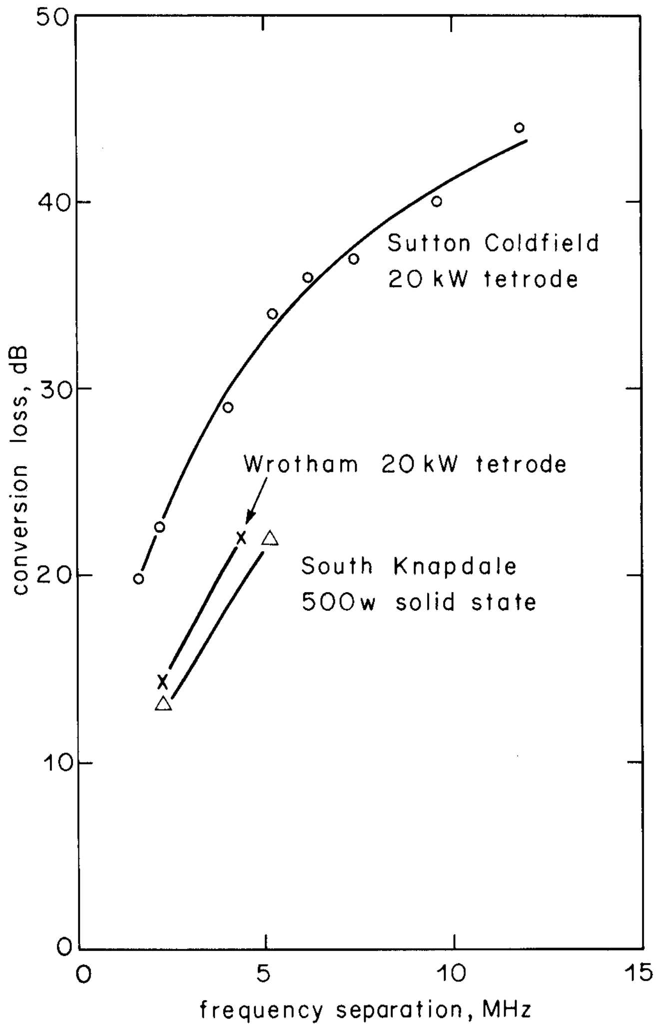

Fig. 4 — Measured transmitter conversion losses.

use in the U.K. for combining two or more broadcast transmitters into a common antenna but only one type will be described in detail by way of illustration. This type of design has been used recently for both high- and low-power installations

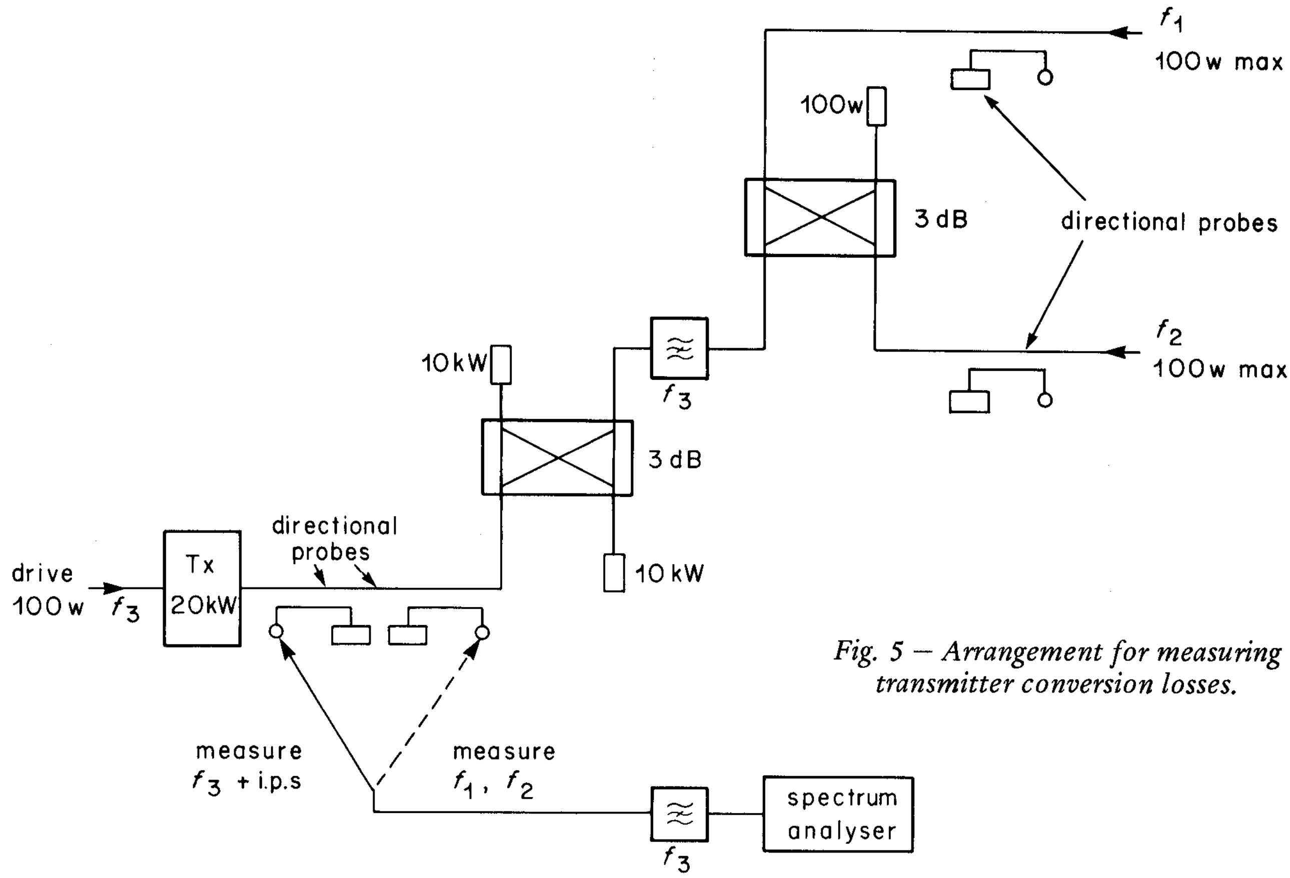

Fig. 5 – Arrangement for measuring transmitter conversion losses.

and is shown schematically in Fig. 6. It may be seen that there are two sections comprising 3 dB directional couplers connected together by equal-length lines carrying resonators. The couplers are of the type in which the outputs from a single input are in phase quadrature. The cross-losses from transmitter T_1 to transmitters T_2 and T_3 at frequency f_1 are determined by the Q of the f_1 resonators, which is related to their physical size, and by the matching of their transmission characteristics. The same is true of the cross-loss from transmitter T_2 to transmitter T_3 at frequency f_2. However, the cross-losses from transmitter T_3 to transmitter T_2 and from T_2 and T_3 to T_1 are determined solely by the balance of the 3 dB couplers. This means that, if no other factors were involved, the levels of the inter-modulation products $2f_2 - f_3$, $2f_1 - f_2$ and

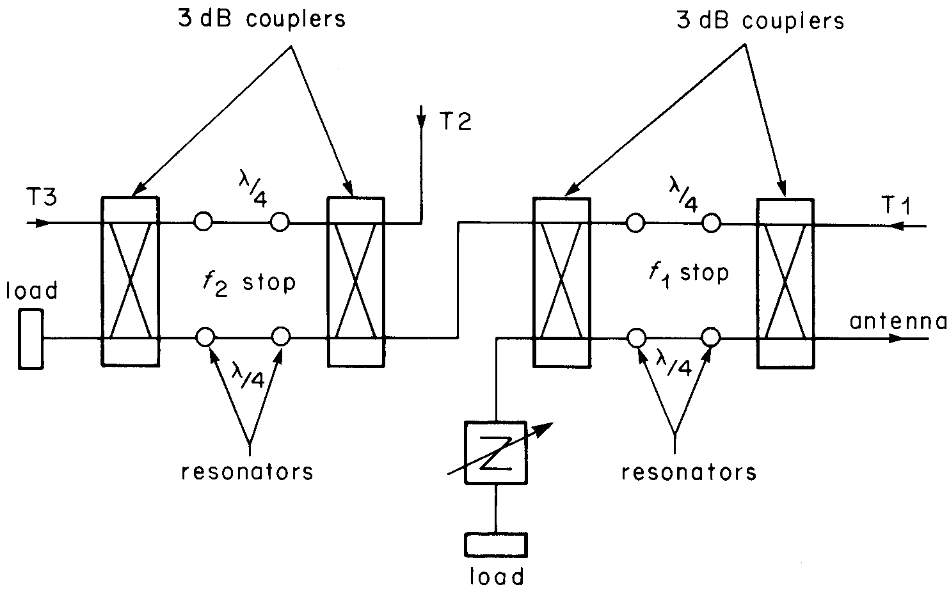

Fig. 6 – A three-frequency combining unit.

$2f_1 - f_3$ could be relatively high. However intermodulation products generated in T_1 and T_2 are diverted to the load and so couple weakly with the antenna. The net result of these factors may be seen from Table 1 where the levels of intermodulation products are calculated from cross-loss measurements made at Wrotham.

made on the same day. The methods of measurement are shown in Fig. 7.

It may be seen from Table 2 (overleaf) that, with the exception of Wrotham, the levels of the $f_1 - \Delta$ and $f_3 + \Delta$ terms are in the neighbourhood of −80 dB while those of the $f_1 - 2\ \Delta$ and $f_3 + 2\ \Delta$ are nearer − 90 dB. This difference is ascribed to the frequency selectivity of the output circuit of the transmitter in which the term is generated. It is also an indication that the levels of the $f_1 - \Delta$ and $f_3 + \Delta$ terms are determined by intermodulation taking place in the transmitters and not to any great extent elsewhere.

TABLE 1

Calculation of i.p. Levels

Frequency	Cross-Loss	Conversion Loss (Assumed)	Loss to Antenna	Relative Level of i.p.
$2f_1 - f_3$	T_1, T_3 @ f_3 −51 dB	−22 dB	$T_1 \rightarrow$ ant @ $2f_1 - f_3$ −36 dB	−109 dB
$2f_1 - f_2$	T_1, T_2 @ f_2 −63 dB	−14 dB	$T_1 \rightarrow$ ant @ $2f_1 - f_2$ −15 dB	−92 dB
$2f_3 - f_2$	T_3, T_2 @ f_2 −88 dB	−14 dB	$T_3 \rightarrow$ ant @ $2f_3 - f_2$ −0 dB	−102 dB
$2f_3 - f_1$	T_3, T_1 @ f_1 −72 dB	−22 dB	$T_3 \rightarrow$ ant @ $2f_3 - f_1$ −0 dB	−94 dB

Some refinements to the arrangement of Fig. 6 are possible. First, additional notch filters may be added to attempt greater suppression of particular i.p.s. Whilst in principle it would be possible to attenuate the i.p. directly on the antenna feeder, it will usually be preferable to fit the notch filter to the ouput of the generating transmitter, where the total power level is lower. Another refinement is to adjust the impedance of the load on the section closest to the antenna as shown in Fig. 6. This has the effect of controlling the level of frequency f_2 that reaches transmitter T_1 and so affects the level of the i.p. at frequency $2f_1 - f_2$.

6. Measurements of intermodulation product levels at representative broadcast transmitting stations

In the UK the majority of network stations transmit three equally-spaced frequencies from a common antenna. Measurements of i.p.s made at a selection of these stations are shown in summary in Table 2 and include examples of high, medium and low-power stations. Two of the stations are newly built, the remainder were built between 15 and 30 years ago. In each case the measurements were made on forward-wave directional couplers installed in the combiner output feeders. At some stations these measurements were supplemented by measurements of the radiated levels

The policy of the BBC at the time the stations described as "old" were built was to suppress intermodulation products to a much higher degree than that required by the Radio Regulations (see Section 8) in order to protect mobile services then using frequencies below 88 MHz and above 97.6 MHz. The target was in fact a relative level of −100 dB[3]. This was never achieved in spite of a detailed investigation into some of the mechanisms by which intermodulation products are generated. Nevertheless, the levels achieved were, and for the most part still are, appreciably lower than those required by the Radio Regulations.

There are two stations in the list described as "new"; both are about two years old. The high-power station, Wrotham, has recently been the subject of an investigation that has brought about a further reduction in the levels of intermodulation products. It may be seen that these levels are now about 10 dB lower than those at the other stations and this is indicative of what can be achieved by

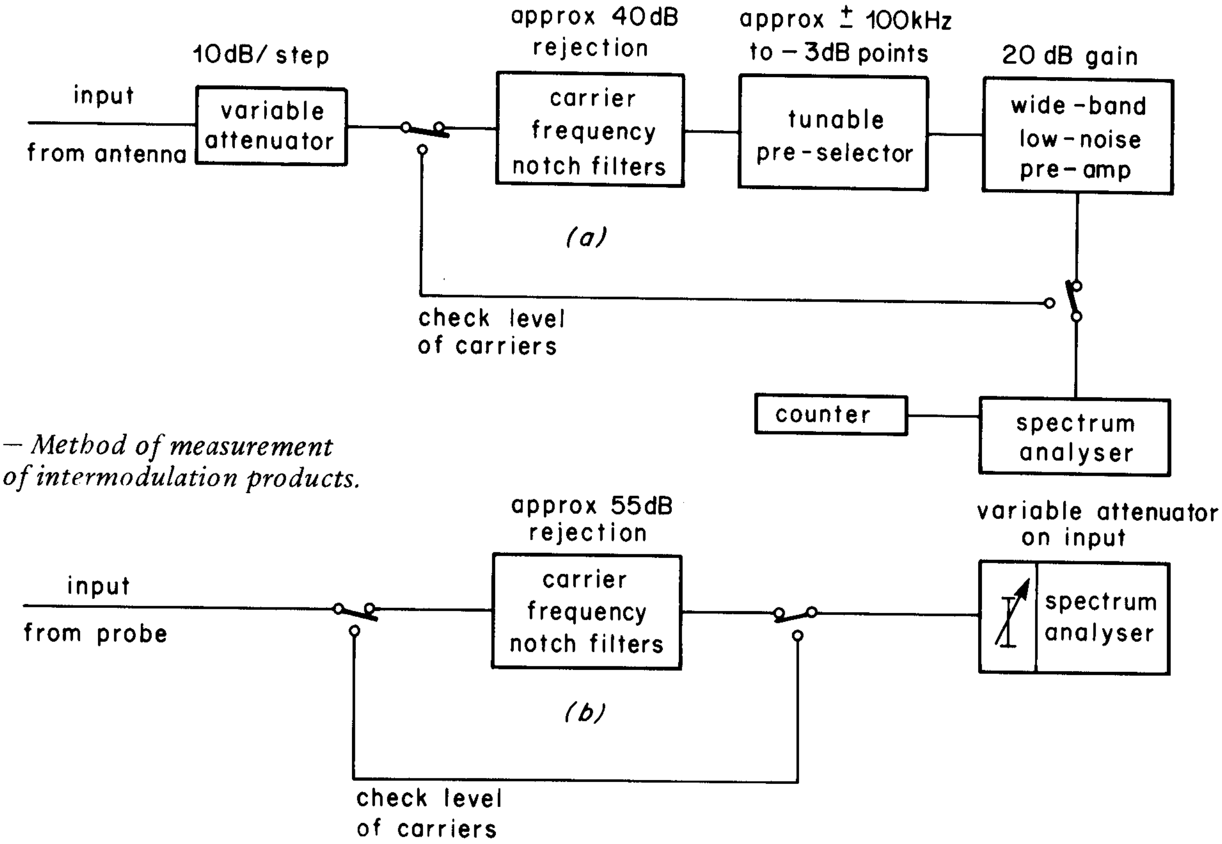

Fig. 7 – Method of measurement of levels of intermodulation products.

TABLE 2

Measurements at stations with regularly spaced channels

Station and Type of Combiner	Relative Level of Intermod Product (dB) $f_1 - 2\Delta$	$f_1 - \Delta$	$f_3 + \Delta$	$f_3 + 2\Delta$	Where Measured	Notes
Wrotham	–104	–94	–102	–102	Feeders	
(New; High Power)	–104	–93	–102	–104	Field	
Tacolneston	–90	–81	–79	–86	Feeders	
(Old; High Power)	–96	–82	–80	–86	Field	
Sutton Coldfield	–102	–87	–76	–87	Feeders	1
(Old; High Power)						
Oxford	–96	–82	–81	–90	Field	2
(Old; Medium Power)						
Peterborough	–94	–83	–82	–90	Feeders	3
(Old; Medium Power)	–87	–71	–76	–86	Field	
Belmont	–94	–88	–82	–88	Feeders	4
(Old; Medium Power)						
IBA Croydon		–82	–80		Feeders	5
(Old; Medium Power)						
Cambridge	–72	–78	–75	–72	Feeders	
(Old; Low Power)						
Northampton	–70	–82	–86	–78	Feeders	
(New; Low Power)						

Notes

1. These measurements were made before the transmitters referred to in Section 4 were brought into service.
2. Oxford has a forth frequency but its intermodulation products were not seen.
3. The reason for higher levels measured in the field is not understood.
4. One frequency at Belmont is displaced by 0.1 MHz. Only the highest levels of products have been noted.
5. Only two frequencies are transmitted.

careful design and good engineering. It also shows that terms generated extraneous to the transmitters are at least as low as this. However it has yet to be demonstrated that such levels can be maintained in service without inordinate effort.

Where one antenna radiates several transmissions that are not equally spaced, intermodulation products are generated on many more frequencies. This is the situation at Wenvoe where there are four transmission frequencies. Measurements at this station are of particular interest in that they give levels of some two- and three-frequency products separately. The results are shown in Table 3. It may be seen that the levels of the three-frequency terms are comparable to those of the two-frequency terms whereas it had been expected that they would be an order of magnitude lower. The reason for this is not understood and merits further investigation.

7. Improvement of existing broadcast transmitting stations

None of the existing national network stations in the UK is capable of giving third-order intermodulation products at frequencies above 108 MHz. If the fourth Stockholm network (with frequencies in the sub-band 97.6–99.8 MHz) were to be implemented at existing network

TABLE 3

Measurements at Wenvoe (four channels, one irregularly spaced)*

MHz	Intermod Composition	Level of Intermodulation Product (dB) Feeder	Field
83.0	$2f_1 - f_4$	–89	–89
85.2	$f_1 + f_2 - f_4$	–90	–93
85.5	$2f_1 - f_3$	–95	–97
87.4	$2f_2 - f_4; f_1 + f_3 - f_4$	–91	–92
87.7	$2f_1 - f_2; f_1 + f_2 - f_3$	–79	–79
89.6	$f_3 + f_2 - f_4$	Not measurable	
89.9	f_1 (carrier)	0	0
91.8	$2f_3 - f_4$	Not measurable	0
92.1	f_2 (carrier)	0	0
92.4	$f_1 + f_4 - f_3$	Not measurable	
94.3	f_3 (carrier)	0	0
94.6	$f_1 + f_4 - f_2; f_2 + f_4 - f_3$	Not measurable	
96.5	$2f_3 - f_2; f_3 + f_2 - f_1$	Not measurable	
96.8	f_4 (carrier)	0	–2
98.7	$2f_3 - f_1$	–94	–90
99.0	$f_4 + f_3 - f_2; f_4 + f_2 - f_1$	–80	–84
99.3	$2f_4 - f_3$	–87	–93
101.2	$f_4 + f_3 - f_1$	–82	–88
101.5	$2f_4 - f_2$	–97	–101
103.7	$2f_4 - f_1$	–90	–98

*Wenvoe is a high power station with an old-type combiner.

stations, some stations could give rise to intermodulation products at frequencies in the aeronautical bands. The same is true of a possible network with frequencies in the sub-band 99.8 – 102.0 MHz. However, the UK administration has indicated that no allocation of these networks can be expected in the near future. Accordingly, by the time these additional frequencies are brought into use all the network stations concerned are likely to have been rebuilt to a new specification. There are, however, some local radio stations under construction where the antenna is shared by one service in the frequency band 94.6 MHz – 97.6 MHz and another in the frequency band 102 MHz – 104.5 MHz so that the third-order intermodulation products could fall in the frequency bands used by ILS and VOR services. The stations concerned are of relatively low power (effective radiated powers of 3 kW) and are not expected to give rise to any significant interference. However if it should be found that there is interference, there should be no great difficulty in fitting suitable filters.

8. Specification of future broadcast transmitting stations

It has been shown above that it is possible to design and build broadcast transmitting stations that will have intermodulation products suppressed to a level lower than that required by Radio Regulations and that such levels can be maintained over a long period of time. It has also been shown that still lower levels may be obtained at individual stations where the additional cost and effort are justified. It remains to be seen whether these levels can equally be maintained in service.

In deciding what the target level should be for radiated intermodulation products it is also necessary to consider the standards being adopted by the aeronautical equipment manufacturers. It was pointed out in Section 1 above that intermodulation will occur in the aircraft receiving equipment also. The most economical arrangement for both the broadcasting and the aviation industries is when both mechanisms appear simultaneously in the ILS/VOR receiver at a certain range of aircraft from transmitters. Put in another way, it will be useless for the broadcaster to achieve a high degree of suppression of intermodulation products unless matched by a corresponding improvement of the performance of the aircraft receiver.

The ITU Radio Regulations[4] require that the mean power of an intermodulation product supplied by a transmitter of mean power above 25 Watts to the antenna transmission line shall be at least 60 dB below the wanted signal and shall not exceed 1 mW. Thus for a transmitter power of 1 kW the highest relative level for the i.p. is –60 dB while for one of 40 kW (the highest transmitter power likely to be used for Band II in the UK) the relative level must not exceed –76 dB. From Tables 2 and 3 it may be seen that most of the old stations exhibit i.p. levels 5 dB or more below the ITU requirement and the two new stations can achieve even lower levels, at least in the short term. It seems likely, therefore, that levels at least 10 dB below the ITU requirement can be achieved and maintained in service for transmitters of 25 Watts or more. For transmitters of powers below 25 Watts it is believed that no improvement is necessary. Table 4 compares these attainable levels with the ITU requirements for different transmitter powers. It may be seen that the relative level attainable at the higher power corresponds approximately with that assumed at the Regional Administrative Conference for FM Sound Broadcasting held in Geneva in 1982.

In order to calculate the corresponding interference ranges for the Type A1 mechanism it is necessary to make assumptions about the effective gain of the transmitting antenna; this is done in Table 5, assuming free-space propagation[5]. It is also assumed that, in calculating the interference range, the effective e.r.p. for mixed polarization is 1 dB greater than that of the horizontal component in accordance with Clause 5.3.6 of the Conference report and that the aircraft is flying in the maximum of the broadcast antenna vertical radiation pattern.

9. Techniques for achieving the required suppression of intermodulation products

In order to achieve or exceed the above supression it is necessary to design and engineer the transmitter installation with meticulous attention to detail. This section gives guidance on aspects that have been found to be important.

9.1. Combining Units

The required isolation between transmitters sharing an antenna should be calculated taking into account the conversion loss at the transmitter and any attenuation in the combiner of the intermodulation product as discussed in Section 5 above. It is recommended that the specification be designed to give a level of i.p. 10 dB lower than that desired, i.e. 20 dB below the requirement of the existing Radio Regulations. This will give a margin for the addition of intermodulation products generated in different ways

TABLE 4

Target levels of i.p.s

Transmitter Power kW	Maximum Level of i.p. relative to main transmission		
	ITU Requirement	Target Level	Target improvement over ITU requirement
0.01	−56 dB	−56 dB	0 dB
0.02	−59 dB	−59 dB	0 dB
0.1	−60 dB	−70 dB	+ 10 dB
0.2	−60 dB	−70 dB	+ 10 dB
1.0	−60 dB	−70 dB	+ 10 dB
4.0	−66 dB	−76 dB	+ 10 dB
10.0	−70 dB	−80 dB	+ 10 dB
20.0	−73 dB	−83 dB	+ 10 dB
40.0	−76 dB	−86 dB	+ 10 dB

TABLE 5

Range of type A1 interference

Transmitter Power, kW	Antenna length, λ	Total ERP dB (kW)	Attainable relative level of i.p. (dB)	ERP of i.p. dB (kW)	Interference Range, km
0.01	1	−21	−56	−79	4.5
0.02	1	−18	−59	−79	4.5
0.1	2	−8	−70	−80	4.0
0.2	2	−5	−70	−77	5.6
1.0	4	+ 5	−70	−67	17.8
4.0	4	+ 11	−76	−67	17.8
10.0	8	+ 18	−80	−64	25.1
20.0	8	+ 21	−83	−64	25.1
40.0	8	+ 24	−86	−64	25.1

It may also be thought advantageous, for reasons of economy, to distinguish between those parts of the installation that can give third-order i.p.s in the ILS/VOR band and those that cannot.

9.2. Antennas

If transmitters are fed into separate antennas, the mutual coupling between them should be taken into consideration when deciding what additional filters will be required.

If a common antenna is used, one having a large aperture and a relatively low power density would be expected to have a better linearity than a small-aperture, high-power density antenna. The more directional vertical radiation pattern of a large-aperture antenna will also be advantageous in restricting radiation towards aircraft.

9.3 Antenna transmission line

The use of multiple contacts in a transmission line should be minimised as these may become non-linear with oxidation. Thus a continuous semi-flexible transmission line would be preferable to a rigid, sectionalised line.

9.4. Transmitter drives

Any significant coupling between transmitter drives, albeit at low level, can give rise to i.p.s. which will degrade the overall performance. If a number of drives are mounted close together the electro-magnetic screening should be of a high standard. Similarly, if the co-axial transmission lines are run together, e.g. in a duct, the screening between the lines should be of a high order; it may be necessary to use a feeder having a solid outer

conductor in order to achieve this. It will in any case be necessary to screen the drives from the field radiated from the antenna. Measurements of this mode of generation of intermodulation products were made by injecting a second frequency onto the low level (0 dBm) transmitter drive; the level of the intermodulation product relative to that of the wanted signal was measured on the transmitter output. The conversion loss for this mode increased with increasing frequency spacing, being about 20 dB for a 2.2 MHz frequency spacing. Accordingly, if it is desired to reduce radiated levels of intermodulation products below −95 dB it is necessary to ensure that any stray pick-up on the transmitter drive is less than −75 dB relative to the wanted signal.

9.5 Directional couplers

These should be designed so that the resistors are very conservatively rated, to avoid the generation of i.p.s within the monitoring equipment[6].

10. Conclusions

It has been shown that it is both possible and practicable at a modern high-power broadcast transmitting station to reduce the levels of radiated intermodulation products to levels at least 10 dB below that required by the ITU Radio Regulations. In the short term it is possible to achieve even lower levels but it has still to be demonstrated that these can be maintained in service over a long period of time. In many cases the efforts of the broadcaster to reduce the radiated levels of intermodulation products would need to be complemented by reductions in the levels of receiver-generated intermodulation if the full benefits are to be realised.

11. Acknowledgements

Measurements on transmitters were made with the help and advice of Dr. R.G. Manton and Mr. P.R. Lamb of Transmitter Capital Projects Department. All measurements at transmitter stations were made with the co-operation of the Transmitter Managers concerned. The co-operation of IBA staff at Croydon is also gratefully acknowledged.

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